

# The formation of narrow X-ray line spectra from realistic hydrodynamical models: applications to the problem of warm absorbers

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**Abstract.** We calculate a series of synthetic spectra from outflows originating from the obscuring torus in active galactic nuclei (AGN). Such modeling includes 2.5D hydrodynamical simulations of an X-ray excited torus wind, including the effects of X-ray heating, ionization, and radiation pressure. 3D radiation transfer calculations are performed in the 3D Sobolev approximation. Synthetic X-ray line spectra and individual profiles of several strong lines are shown at different inclination angles, observing times, and for different characteristics of the torus.

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## INTRODUCTION

Radiation transfer calculations provide a connection between the results of dynamical models and observations of photon spectra. In this talk I will present calculations of 3-dimensional transfer calculations using the generalized Sobolev approximation. These will be illustrated with applications to evaporative outflows originating from the obscuring torus in active galactic nuclei (AGN). These outflows provide a likely explanation for the rich 'warm absorber' spectra observed with recent X-ray telescopes, and these spectra provide quantitative constraints on the nature of the flow. We have calculated 2.5D hydrodynamical simulations of an X-ray excited torus wind, including the effects of X-ray heating, ionization, and radiation pressure. We will describe the results of 3D Sobolev radiation transfer calculations and show results for various assumptions about the nature of the torus and our viewing direction.

## SOBOLEV RADIATION TRANSFER FROM AN X-RAY EXCITED WINDS IN AGN SUGGESTS SUCH WINDS TO BE THE ORIGIN OF WARM ABSORBERS

### Radiation transfer in spectral lines

The supersonic motion of gas of the AGN wind provides justification for use of the Sobolev approximation while calculating radiation transfer in spectral lines. The primary assumption of the Sobolev approximation is that due to velocity gradients in the flow

the Doppler shifting of frequency moves a photon quickly out of the resonance soon after it interacts with the flow. Thus the radiation transfer in the Sobolev approximation is treated as an entirely local problem, assuming the characteristics of the absorbing plasma are constant across the narrow region of interaction. Our hydrodynamical model is axially symmetric, but this symmetry is lost if viewed from an inclination angle, so to calculate the spectrum we must adopt a 3D Sobolev approximation. Even if the poloidal velocity along the streamline is monotonically increasing, the *projected velocity* may not behave in such a way, rather having a maximum or several maxima (depending on the real structure of the 2D flow). This poses the problem of multiple resonances which we discuss in detail below.

The geometry of the problem is shown in Fig.1. The Cartesian coordinate system  $xyz$  ( $y$  axis is not shown) is located at  $O$ . The observer is situated at infinity looking at the torus from an inclination,  $\theta_0$ . Since the hydrodynamical model is axially-symmetric, we put the observer in the  $xz$  plane. The plane of the sky,  $PS$ , is transported to  $O$ , providing another Cartesian coordinate system  $x'y'z'$ , ( $y'$  axis is not shown) which is the  $xyz$  system, rotated by the angle  $\theta_0$  around the  $y$  axis. Notice also that  $y' = y$ . Our assumptions imply (see further in the text) that a photon after being scattered in a spectral line, for example, in the point  $R$ , propagates along the straight line  $RB$  in the direction of the unit vector  $\mathbf{n}$ . This ray,  $RB$  intersects the plane  $PS$  at the point  $A$ , being at the angle  $\phi_0$  from the  $OZ'$  axis and at a distance  $p$  (impact parameter) from  $O$ . Summing all such possible rays, i.e. integrating over the plane,  $PS$ , the radiation flux which is observed at infinity is obtained.

## Methods

To calculate an X-ray line spectrum from the moving gas which was stripped off the AGN torus via X-ray induced evaporation, we combine together the following ingredients:

- i) Taking into account heating and cooling processes we calculate a set of time-dependent 2.5D hydrodynamical models of winds evaporated from the AGN torus.
- ii) Based on the 3D generalization of the escape probability method, we construct a numerical code which is able to calculate line spectra from a 3D flow.
- iii) Making use of the XSTAR code we calculate tables of X-ray opacities for different energies and ionization parameters.
- iv) Using opacity tables and distributions of density, and velocity from hydrodynamical models, we calculate the emergent spectrum.

Step i) has been described in [1]. In the following we briefly review methods and describe results of steps ii) through iv).

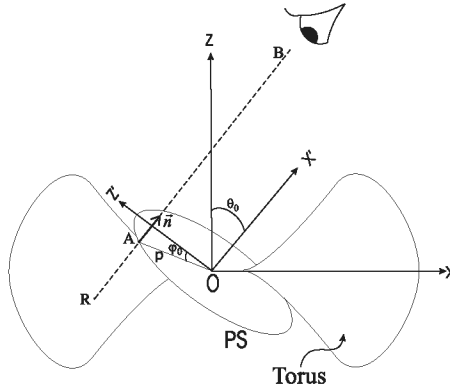
In the presence of multiple resonances, distant points within the flow are causally connected, i.e. they can exchange photons ranging within the line frequency width. In terms of surfaces of equal frequencies, such surfaces become multi branched, allowing for a photon of a frequency  $\nu^\infty$  to interact with the moving matter at different points along a single line of sight. In the presence of multiple resonance surfaces, we assume that the interaction between  $\sigma_{i-1}$  and  $\sigma_i$  takes place only in the forward direction (in the direction towards the observer). All other possible interactions are neglected. Then the expression for the intensity should be just summed over the available resonance surfaces.

Altogether, these assumptions are known as the *disconnected approximation*:

$$I^\infty(\nu^\infty) = I^{\text{ins},0} e^{-\sum_i^N \tau_{li}} + \sum_i^N S_i (1 - e^{-\tau_{li}}) e^{-\sum_j^{N-1} \tau_{lj}}, \quad (1)$$

where  $N$  is the total number of resonances and  $I^{\text{ins},0} = I_{\text{src}} e^{-\tau_{es}(\mathbf{r}_0)}$  is the initial intensity of the radiation at the point  $\mathbf{r}_0$ , which is the farthest point along the ray from the observer in the computational domain,  $I_{\text{src}}$  is the intensity emitted by the source (core), and for simplicity, we omit the dependence of  $I$  on  $p$ ,  $\phi_0$ , and  $\theta_0$ ;  $\tau_{es}$  is an electron scattering optical depth:

$$\tau_{es}(\mathbf{r}) = \int_0^r \kappa_{es} \rho \, dr. \quad (2)$$

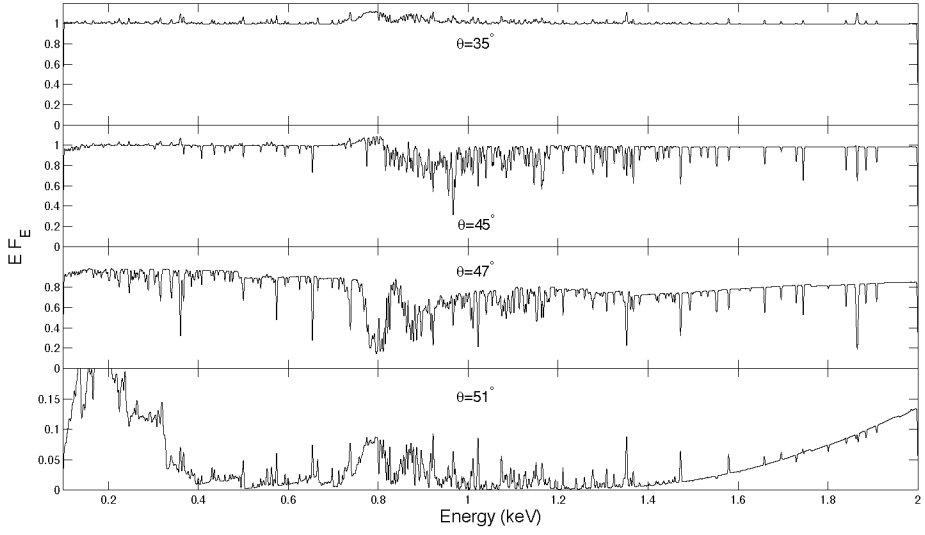


**FIGURE 1.** Illustration of the geometry and coordinate systems implied by the calculations (see text for details). Notice, that the  $y$ -axis (not shown) points into the plane of the picture to form a right-handed  $xyz$  coordinate system, and  $y' = y$ . Not to scale.

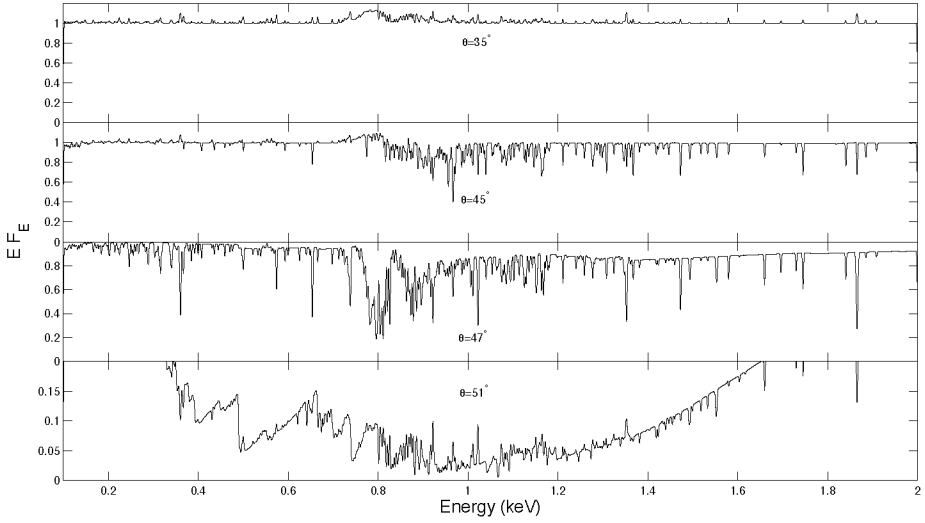
## RESULTS

The major goal of this paper is to calculate emission and absorption spectra predicted by hydrodynamical simulations. The maximum density of the initial torus,  $n_{\text{max}}$ , or, alternatively, its initial Compton optical depth  $\tau_{\perp}^C = \tau(\theta = 90^\circ)$  is used as a parameter to distinguish between different models;  $n_{\text{max}}$  roughly scales with the column density of the absorbing gas during the evolution of the torus.

Our modeling of the spectra use a set of pre-calculated hydrodynamical models, including combinations for:  $\tau_{\perp}^C = 1.3$  (models  $A_i$ ), and  $\tau_{\perp}^C = 40$  (models  $B_i$ ); equivalently, these correspond to initial tori, having  $n_{\text{max}} = 10^7 \text{ cm}^{-3}$  or  $n_{\text{max}} = 10^8 \text{ cm}^{-3}$ . Other parameters, determining the torus are  $R_0$  and the distortion parameter,  $d$ . Models  $A_i$  and  $B_i$  have  $d = 2.5$ . Additionally there are two models with  $d = 5$  (models  $C_i$ ) which represent an extreme case of extended and rarified torus. The full list of models is given in the Table 1 of [2].



**FIGURE 2.** Model  $B_6$  ( $\tau_{\perp}^C = 40$ ,  $R_0 = 1\text{pc}$ ) X-ray spectra, observed at  $t = 4$  as a function of angle.



**FIGURE 3.** Model  $B_3$  ( $\tau_{\perp}^C = 40$ ,  $R_0 = 0.5\text{pc}$ ) X-ray spectra, observed at  $t = 4$  as a function of angle. Note a different scale in the y in the plot at the bottom; at  $\theta > 55^\circ$  the X-ray flux is strongly suppressed by the Compton thick cold matter.

We have carried out 3D radiation transfer simulations of the absorption-emission spectra produced by the X-ray excited wind from the obscuring torus in AGN. As a previous stage of our research we performed time-dependent 2.5D numerical simulations of wind which originates from cold, rotationally supported torus whose inner throat is exposed to a strong ionizing radiation of the BH accretion disk [1, 2]. Previous results, including purely absorption spectra from such flow, suggest that this model is promising in establishing cold tori as a major source of the warm absorber flows observed in many AGN.

Motivated by the fact that in case of an extended wind a 1D transmission approximation for the radiation transfer in lines is inadequate, we relax this approximation by performing 3D simulations of the radiation transfer in X-ray lines in a moving gas of the torus wind. The distribution of the gas is obtained from the hydrodynamical modeling which is used as an input to the radiation transfer calculations carried out making use of a 3D generalization of the Castor escape probability formalism.

Our synthetic spectra contain many lines, some with strong absorption as well as emission lines from O, Mg, Si, Ne, and Fe. In general, features observed near 13.7 – 13.9 (892 - 905 eV), 9.3 – 9.4 (1319 - 1333 eV), and 6.7 – 6.9 (1797 - 1831 eV) are likely due absorption from high ionization Ne, Mg and Si, respectively. Observations also suggest a simultaneous presence of the gas at a low ionization state,  $\log \xi \simeq 0$  and a high ionization component with  $\log \xi \simeq 100$ . There are also claims of observational evidence which ruling out the existence of gas at intermediate ionization parameters for some objects. Gas at ionization parameters outside the range  $0 \leq \log(\xi) \leq 3$  is harder to detect unambiguously from observations.

## ACKNOWLEDGMENTS

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## REFERENCES

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